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Abstract

Grounded (embodied) theories of cognition propose that memory, including knowledge and meaning, is grounded in sensorimotor and mental state processes. The main proposed mechanism for how memory is grounded is mental simulation. Simulation occurs when neural activity in modal association cortex triggers time-locked, recurrent and feedback activity across multiple lower-level modal processing areas from which the memory was initially constructed. Through this distributed multi-regional activity, seeing an object or reading its name (e.g., "dog") re-enacts associated features that were stored during earlier learning experiences (e.g. its shape, color, motion, actions with it), thereby constructing cognition, memory, and meaning. This paper reviews convergent evidence from cognitive neuroscience of mental imagery, object cognition, and memory that supports a multi-state interactive (MUSI) account of automatic and strategic mental simulation mechanisms that can ground memory, including the meaning, of objects in modal processing of visual features.

Keywords: Embodiment, grounded cognition; category; concept; meaning, memory; shape; object; vision; brain.

The MUSI account of the brain dynamics of visual object cognition proposes that posterior object processing areas activate at different times in at least 3 states performing distinct functions (Schendan & Ganis, 2012; Schendan & Kutas, 2007). In state 1, initial activation of object processing cortex feeds forward from occipital to anterior temporal cortex. In this state, from ~120 to 200 ms, an object is perceptually categorized coarsely for the first time (Ganis & Schendan, 2008; Ganis, Smith, & Schendan, 2012; Schendan & Ganis, 2013; Schendan, Ganis, & Kutas, 1998). An event-related potential (ERP) that localizes to occipitotemporal cortex, the N170/VPP, shows the first clear object-sensitivity (i.e., greater for intact objects than scrambled versions depicting no figure), which is a hallmark of this cortex using functional magnetic resonance imaging (fMRI) (Schendan & Lucia, 2010; Schendan & Stern, 2007). However, cognitive factors (e.g., mental imagery, category decision success, meaning, semantic context) modulate this cortex sensitively in fMRI studies but do not likewise affect the N170/VPP (e.g., Ganis & Kutas, 2003; Schendan & Lucia, 2009; Schendan & Lucia, 2010; Schendan & Maher, 2009). Thus object information activated in state 1 supports categorical perception, but cognition that enables complex behavior (e.g., deciding the object is a member of the dog category) does not start until later, in a second state.

State 2 operates from ~200 to 500 ms when occipitotemporal cortex is activated again but in a sustained, interactive manner dominated by feedback and recurrent processing among these areas and with ventrolateral prefrontal cortex (VLPFC). The frontal N3(00) complex is the first ERP to reflect activity in occipitotemporal cortex related to the success of visual object cognition. Like the N170/VPP (state 1) and fMRI activation, the N3 is object-sensitive, category-specific, and shows adaptation effects (Ganis & Schendan, 2008; Schendan & Ganis, 2012; Schendan & Lucia, 2010). However, unlike state 1 but like occipitotemporal and VLPFC activity in fMRI, the N3 varies dramatically with mental imagery and factors affecting category decision success, such as stimulus typicality and impoverishment, implicit memory, knowledge, and meaning (Ganis & Kutas, 2003; Philiastides & Sajda, 2007; Schendan & Ganis, 2012; Schendan & Kutas, 2002, 2003, 2007; Schendan & Lucia, 2009, 2010; Schendan & Maher, 2009; Schendan & Stern, 2008; Voss, Schendan, & Paller, 2010). Later from 300 to 500 ms, the centroparietal N400 reflects semantic memory activation related to processing word-related information in anterior temporal cortex and VLPFC (Kutas & Federmeier, 2011). Intriguingly, N3 effects start and peak before those on the N400, placing the N3 in a temporal position to reflect processes supporting mental simulation of object information that constructs the meaning analyses indexed by the N400. State 2 reflects decision, implicit memory, knowledge, and meaning processes distinct from earlier state 1 and later state 3 processes.

State 3 operates from ~400 to 900 ms during complex cognitive tasks and evaluates internally the accuracy of earlier and ongoing decision processes and executes verification processes, including effortful, strategic, conscious mental simulations. These brain dynamics are reflected in a centroparietal late positive complex (LPC) that distinguishes between correct and wrong decisions but does not vary with how well the stimulus matches memory, which, by contrast, sensitively modulates the N3 (Schendan & Kutas, 2002; Schendan & Maher, 2009). The LPC varies with episodic recollection, as when recalling details of the learning experience during recognition and mental imagery tasks (Rugg & Curran, 2007; Schendan & Ganis, 2012), as does a default mode network that connects strongly with the mediotemporal system for episodic memory and is associated with episodic simulation and strategic, conscious mental imagery (Ganis & Schendan, 2011; Schacter, Addis, & Buckner, 2008). Such late processes, however, may also support complex semantic analysis (e.g., Sitnikova, Goff, & Kuperberg, 2009). Thus the LPC reflects internal evaluation and verification processes that also support strategic, conscious, goal-driven mental simulation that can contribute to grounding cognition in more abstract and complex ways than earlier automatic mental simulation.

The MUSI account can explain object cognition as well as the brain mechanisms of mental simulation to ground cognition in visual object processing, positing two functionally-distinct states of mental simulation: Earlier automatic simulation and later strategic simulation (Schendan & Ganis, 2012). Crucially for grounded cognition theory, the pattern of mental imagery findings on the N3, N400, and LPC resembles that for repetition priming of perceived pictures, implicating these ERPs as markers of mental simulation. Following initial categorical perception of objects in state 1, interactive, top-down and reflexive feedback, and recurrent processes in state 2 support automatic mental simulation to ground knowledge and meaning (Barsalou, 2009) in modal processing of visual features in occipitotemporal cortex (N3) and word-related semantic processes in anterior temporal cortex (N400). The second type of mental simulation is strategic, goal-directed, and conscious and recruited when the task demands internal evaluation of cognition, as in mental imagery and episodic memory tasks. This simulation reflects intentional top-down processes directed by lateral prefrontal and posterior parietal networks for attention, cognitive control, and working memory (LPC). These neural markers of automatic and strategic mental simulation should be the focus of needed research into the brain mechanisms for how modal information processing grounds cognition.

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